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DUST BOMBARDMENT ON THE LUNAR SURFACE

by Curtis W. McCracken

Goddard Space Flight Center

and

Maurice Dubin

NASA Headquarters



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Curtis W. McCracken

Goddard Space Flight Center
Greenbelt, Maryland

and

Maurice Dubin

NASA Headquarters
Washington, D.C.

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SUMMARY

Various types of observational data which are available for the vicinity of the earth and for interplanetary space are reviewed and evaluated in an attempt to establish a good estimate of the flux of small interplanetary dust particles impacting on the moon. A porous, low-density surface layer consistent with photometric and radiometric observations is assumed to exist on the moon, and the effects of the impacting dust particles are considered.

The interplanetary particulate material accreted by the moon amounts to approximately 1 gm/cm^2 for dust particles with masses less than 10^4 gm if the flux has remained constant during the past $4.5 \times 10^9 \text{ yr}$. This value for the accretion rate represents a lower limit if the flux has decreased appreciably since the time of formation of the major lunar surface features.

The porous surface layer acts as a protective covering against hypervelocity impacts of small dust particles and inhibits the production of high speed spray particles which could escape from the moon. The surface layer therefore consists of a mixture of lunar and interplanetary material. The hypervelocity impacts of dust particles constitute an effective mechanism for development and maintenance of a dendroid surface layer of high porosity and low density.



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(Manuscript Received June 3, 1963)

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Curtis W. McCracken

Goddard Space Flight Center

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INTRODUCTION AND STATEMENT OF THE PROBLEM

The moon, like the earth, is subjected to a continuing bombardment by interplanetary dust particles having a wide range of sizes. The dust particles impacting on the moon produce markedly different effects, however, than those impacting on the earth. This difference arises because any atmosphere which may be present on the moon is not of sufficiently high density to destroy the particles by vaporization, ablation, or fragmentation (or to decelerate the particles) before they strike the lunar surface. The dust particles impact on the moon at speeds undiminished from their original speeds (relative to the moon). In fact, the speed of a particle at impact is slightly higher than the original speed, as a result of the gravitational acceleration produced by both the moon and the earth.

Dust particles having different origins and different orbital distributions are involved; therefore, the average speed at impact depends (to some extent) on the size of the particle. Typical average speeds are 10 km/sec for dust particles with dimensions of microns, 30 km/sec for particles with dimensions of millimeters, and 15 km/sec for bodies with dimensions of meters. These high speeds lead to hypervelocity impacts, events of explosive violence that result in destruction of both the particle and a portion of the target. The impacting particle and the target material undergo vaporization and fragmentation (or spallation). Most of the fragments and vapors are expelled from the site of the impact. The speeds and ejection angles depend (to a large extent) on the physical structure of the target material and possibly on the structure of the impacting dust particle.

Some of the vaporized and fragmented material may be ejected at speeds greater than the lunar escape speed and, hence, will escape from the moon. The question arises as to whether the moon is gaining or losing mass as a result of bombardment by dust particles. Negative accretion (net loss of mass) requires that the outer layer of the moon is continually being eroded and removed, thereby exposing new surface material. Positive accretion (net gain of mass) could occur through accretion

*This report was presented at the Lunar Surface Materials Conference, Boston, Massachusetts, May 21-23, 1963, and will be published in the proceedings of that meeting.

of interplanetary material but does not necessarily require that no material escapes from the moon. An important consequence of positive accretion would be the formation of a layer of dust and rubble on the lunar surface. If this layer were dendroidal, it could (for certain sizes of impacting dust particles) effectively inhibit the ejection from the moon of fragments and vapors created in a hyper-velocity impact.

There are several external mechanisms besides bombardment by interplanetary dust particles which possibly affect the lunar surface in various manners. These mechanisms include bombardment by solar ultraviolet and x-ray radiation, by solar particles (principally protons and electrons), and by cosmic rays. The effects possibly produced by these mechanisms, as well as the nature of the lunar surface, have been discussed by various investigators, including Öpik, Whipple, and Gold (References 1-3).

The relative importance of dust bombardment in affecting the microstructure of the lunar surface depends on several aspects of the problem. The fluxes of dust particles of various sizes, the physical structure of the dust particles, the nature of the lunar surface, and the type of hypervelocity impact which applies are important in an investigation of the effects of dust bombardment. The topics of fluxes of dust particles, probable nature of the lunar surface, and possible effects of dust bombardment on the lunar surface are reviewed in subsequent sections, by using presently available data.

FLUXES OF INTERPLANETARY DUST PARTICLES ON THE MOON

Widely different estimates of the accretion rate of interplanetary dust particles have appeared in the literature. It is well to investigate in detail the observational data on fluxes of dust particles, because of the possible importance of dust in determining the lunar surface characteristics.

Information concerning the accretion rates of interplanetary particulate aggregates for the moon is directly available only for those bodies that are sufficiently large to produce visible craters on the moon. The limit on telescopic resolution corresponds to a crater diameter of approximately 750 m (0.4 mi.) for photographic observations and 200 m (0.1 mi.) for visual observations, according to Kuiper (Reference 4). Formation of such a crater requires a particulate aggregate having a radius and a mass of about 10 m and 10^{10} gm, respectively, based on the computations of Öpik (Reference 5).

Statistical studies of the frequencies and size distributions of craters on the moon have been made by several investigators, notably Öpik; Shoemaker, Hackman, and Eggleton; McGillem and Miller;* Palm and Strom; and Kreiter (References 6-10). This paper is concerned primarily with the fluxes and effects of particles having masses considerably smaller than those responsible for visible lunar craters, so the subject of crater statistics will not be pursued.

*See also References 11 and 12.

Attention is directed, in general, to bodies having masses less than 10^{10} gm and, in particular, to particles having masses less than 10^4 gm. Indirect approaches must be employed in establishing the fluxes for particles with masses less than about 10^{10} gm. Data which can be used in these indirect approaches are available for two regions of space – the vicinity of the earth and interplanetary space. These regions are sufficiently far from the moon to make the necessary interpolation subject to some uncertainty. Interpolation toward the moon from the two regions for which data are available does, however, permit fairly realistic limits to be set on the fluxes of interplanetary dust particles impacting on the moon.

The approach in establishing the fluxes of dust particles for the moon follows. Relevant data on the fluxes of dust particles in the vicinity of the earth are compiled to give a cumulative mass distribution that is valid for the vicinity of the earth. Portions of this mass distribution are then considered to be valid also for the vicinity of the moon, and the results from studies of the zodiacal light are used to replace the portion of the distribution which probably is valid only near the earth.

It is felt that this procedure leads to a cumulative mass distribution which applies in the vicinity of the moon and is valid for dust particles ranging in size from the smallest particles permitted by solar radiation pressure to remain in closed heliocentric orbits up to particles large enough to produce telescopically visible craters on the moon. Of course, the accuracy of this cumulative mass distribution is order-of-magnitude, because of the uncertainties in the observational data used as a basis for the distribution.

The data from which the fluxes are derived are considerably more accurate and extend over a much larger range of particle mass for the vicinity of the earth than for interplanetary space. An attempt has been made to select some of the most reliable data for use in establishing the fluxes for dust particles of different sizes. The choice of data to be included in the compilation has been influenced by the desire to cover as completely as possible the range of particle mass extending from 10^{10} gm down to 10^{-14} gm. It is believed that the selected data is quite representative of most of the data available in the literature.

Data on the fluxes of dust particles in the vicinity of the earth are obtained with a number of observational techniques. The most suitable data come from studies of the frequency of meteorite falls, observations of meteors with photographic, visual, and radar techniques, and direct measurements made with rockets and satellites. These data are the most reliable for use in establishing a mass distribution that can be considered valid for the vicinity of the earth.

Information about the spatial density of dust particles in interplanetary space has been obtained from photometric studies of the zodiacal light. Reasonable assumptions regarding the mass density and average speed for these particles lead directly to estimates of the flux of small interplanetary dust particles impacting on the moon. Also available is a direct measurement of the flux of dust particles in interplanetary space obtained recently by Alexander (Reference 13) with the probe Mariner II (1962 *ap* 1).

A cumulative mass distribution for the vicinity of the earth (derived on the basis of the selected data) is shown in Figure 1. The data used and the assumptions made in constructing the mass

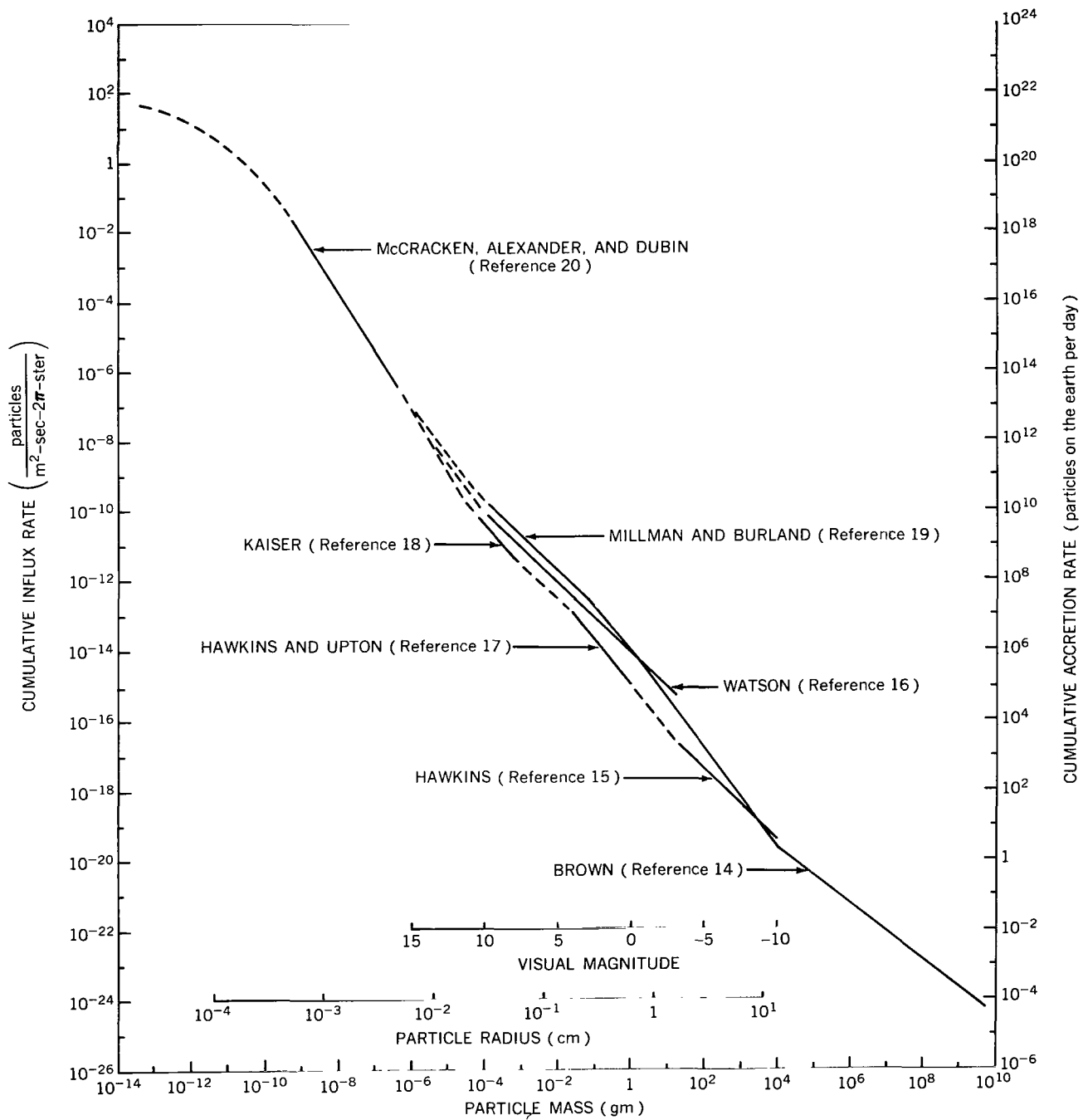


Figure 1—Cumulative mass distribution for interplanetary dust particles in the vicinity of the earth, derived from studies of the frequency of meteorite falls, from observations of meteors, and from direct measurements obtained with rockets and satellites.

distribution are discussed later. In Figure 1 the cumulative flux of particles with mass m and larger is plotted as a function of particle mass. The data obtained from the direct measurements and the studies of meteorite falls are plotted directly in terms of particle mass. The data from meteor observations are plotted in terms of visual magnitude, which is related to the mass of a particle in a manner to be described later. A scale of radius of the particles (computed on the basis of a mass density of 1 gm/cm^3) is included for convenience in referring to the approximate size of a particle.

The results obtained with different observational techniques are generally expressed in terms of different parameters of the dust particles or in terms of different phenomena produced when the dust particles encounter the atmosphere of the earth. Only the studies of meteorites (and micrometeorites, which are not considered here) directly yield information about the masses of the particles. This information is subject to some uncertainty because of the difficulty in estimating the amount of material lost through ablation and vaporization as the particles enter the atmosphere.

Brown (Reference 21) and Hawkins (Reference 22) recently analyzed the frequency of meteorite falls as a function of both the mass of the meteorite and the type of meteorite. The results obtained in these two investigations are in good agreement regarding the rate of infall of large meteorites but are in disagreement about both the fluxes of the small meteorites and the mass distributions of iron and stone meteorites. Only the results of Brown will be considered. Brown gave cumulative mass distributions (in tabular form) for iron and stone meteorites. If the results are combined and the fluxes revised upward by the factor of 3.4 later suggested by Brown (Reference 14), a cumulative mass distribution can be derived for all meteorites incident on the earth. The range of validity is considered here to be 10^4 to 10^{11} gm, although Brown considered the range to be 1 to 10^{11} gm.

The results from direct measurements of fluxes of dust particles with rockets and satellites probably constitute the most reliable data about the fluxes of small dust particles in the vicinity of the earth. These measurements are subject to only small uncertainties (≤ 2) arising from the fact that a value for the average speed of the particles presently must be assumed. Most of the detectors flown have been sensitive to the momentum of an impacting dust particle; hence, an average speed (relative to the detector) must be assumed in order to express the results in terms of particle mass. The available direct measurements have been collected, reviewed, and evaluated in several recent papers (References 20 and 23). The results most probably are not applicable to the moon because of the existence of an enhancement of the fluxes of small dust particles in the vicinity of the earth (Reference 24).

The literature contains a lot of data on the fluxes of dust particles of meteoroidal size. The results come from radar, visual, and photographic observations of both shower and sporadic meteors. Only the data on sporadic meteors need be considered in regard to average fluxes over time intervals longer than 1 yr.

The mass of a particle is not a directly observable parameter in meteor observations; it must be computed on the basis of meteor theory. The observable parameters include electron line density, luminous intensity, and photographic intensity for radar, visual, and photographic meteors, respectively. The observed fluxes for both radar and photographic meteors (for convenience in comparing

the results with the visual observations) usually are expressed also in terms of visual magnitude, which is a logarithmic measure of the luminous intensity. These conversions involve some uncertainties, but the major uncertainty is encountered upon trying to express the results from meteor observations in terms of the mass of a particle. The mass-to-magnitude relation is subject to revision as better values for the parameters used in meteor theory become available.

Watson summarizes the results of early visual and telescopic observations of meteors with visual magnitudes extending from -3 to +10 (Reference 16). The results are given as an incremental magnitude distribution (presented in tabular form) from which a cumulative magnitude distribution can be readily derived.

Millman and Burland reported the results of radar, visual, and photographic meteor observations in Canada (Reference 19). These results indicate that as the brightness increases the number of meteors progressively becomes smaller than would be expected on the basis of the results given by Watson. McKinley has reviewed the Canadian results and given cumulative magnitude distributions (in equation form) derived from the observations (Reference 25). The distributions were extrapolated slightly to cover the range of visual magnitude extending from -10 to +10.

Hawkins and Upton (Reference 17) analyzed a sample of the observations made in the Harvard Photographic Meteor Program. The results were expressed as cumulative magnitude distributions for both photographic and visual magnitudes. The distribution expressed in terms of visual magnitude will be used here, and the range of validity (as read from the plotted observational data) will be considered to extend from 0 to +4.1 in visual magnitude. The cumulative mass distribution given by Hawkins and Upton cannot be used here, because it is based on a different mass-to-magnitude relation than the one adopted for use in this paper.

Hawkins analyzed the available data on fireballs and bright meteors in an attempt to establish the influx rates (Reference 15) and concluded that the number of asteroidal and cometary meteoroids were equal somewhere within the range 0 to -5 in visual magnitude. Hawkins adopted a visual magnitude of -3 as a fiducial point and then used a constant-mass-per-magnitude extrapolation toward brighter meteors (extending to -10 in visual magnitude) as a cumulative magnitude distribution for the fireballs. This same procedure has been followed here by using the cumulative magnitude distribution (expressed in terms of visual magnitude) that was given by Hawkins and Upton (Reference 17). Hawkins also converted the cumulative magnitude distribution to a cumulative mass distribution, but this conversion was based on a mass-to-magnitude relation different from the one adopted here.

Kaiser gave a cumulative flux for radar meteors with radar magnitudes of +10.8 and lower (Reference 18). The gradient of the magnitude distribution was given for meteors with radar magnitudes between +8 and +10.8; a cumulative magnitude distribution can be derived.

The foregoing results from the meteorite studies by Brown, from the meteor observations by Watson, Millman and Burland, Kaiser, Hawkins and Upton, and Hawkins, and from the direct measurements with rockets and satellites were used in constructing the cumulative mass distribution shown in Figure 1. All the results from meteor observations were plotted in terms of visual magnitude. (It was assumed that radar and visual magnitude are approximately equal.) Visual magnitude was then

related to the particle mass by assuming that a meteoroid with a mass of 1 gm and a speed of 30 km/sec will, on the average, produce a meteor with a visual magnitude of zero. This relation between visual magnitude and particle mass was used recently by Whipple in a revision of the mass-to-magnitude relationship (Reference 26). It is particularly convenient, because it matches the zero point of the visual magnitude with the zero point of the logarithmic mass scale.

The cumulative mass distribution shown in Figure 1 is specifically valid for the vicinity of the earth. The segments of the curve which were derived from the studies of meteors and meteorites can be applied readily to the vicinity of the moon, as can be demonstrated by the following argument. The average speed observed for meteors is approximately 30 km/sec. The average speed for the meteorite-producing meteoroids is about 17 km/sec, according to Whipple and Hughes (Reference 27). Such speeds could not have been changed much from the original values by the gravitational effects of the earth. The fluxes of meteoroid-size particles are, therefore, essentially the same for the moon as for the earth. Öpik suggests that the flux at the moon is about 80 percent of that for the earth (Reference 6). Brown comes to a similar conclusion by considering the flux near the earth to be 1.3 times that for the moon (Reference 21). The value given by Öpik is adopted for use here.

Determination of the fluxes of small dust particles presents a problem. As was pointed out, the fluxes measured near the earth with satellites and rockets probably do not apply for the vicinity of the moon. Since no reliable direct measurements have been obtained for the vicinity of the moon, other data must be used for establishing the impact rates of small dust particles on the moon. Data for this purpose are available from studies of the zodiacal light by Allen, van de Hulst, Elsässer, and Ingham (References 28-31). Also available is a direct measurement made with the spacecraft Mariner II as reported by Alexander (Reference 13). The results of Elsässer and Ingham are used here in computing the flux of small dust particles on the moon. The direct measurement is in fair agreement with either of these sets of data.

The results from the photometric studies of the zodiacal light were given as incremental size distributions valid within certain limits on the size of the dust particle. These distributions are integrated between the appropriate limits to yield a cumulative size distribution. A mass density of 1 gm/cm³ and an average speed of 10 km/sec in interplanetary space are applied for conversion from spatial density of particles of a given size and larger to a flux of particles of a given mass and larger which can be used for the vicinity of the moon.

Portions of the cumulative mass distribution shown in Figure 1 are applied to the vicinity of the moon and merged with the distributions derived from the results of zodiacal light studies to yield the distribution shown in Figures 2 and 3. (The flux is expressed in various units in Figures 1, 2, and 3 for convenience in making calculations for different intervals of time.) The distribution derived from measurements made near the earth with satellites is shown as a dot-dash curve in Figures 2 and 3 for the purpose of comparison. The geocentric distance to which the high fluxes measured near the earth apply is not known; the fluxes of small dust particles on the moon probably fall between the values indicated by the zodiacal light studies and the values indicated by the direct measurements obtained in the vicinity of the earth. The fluxes are, however, thought to be close to those indicated by the zodiacal light studies.

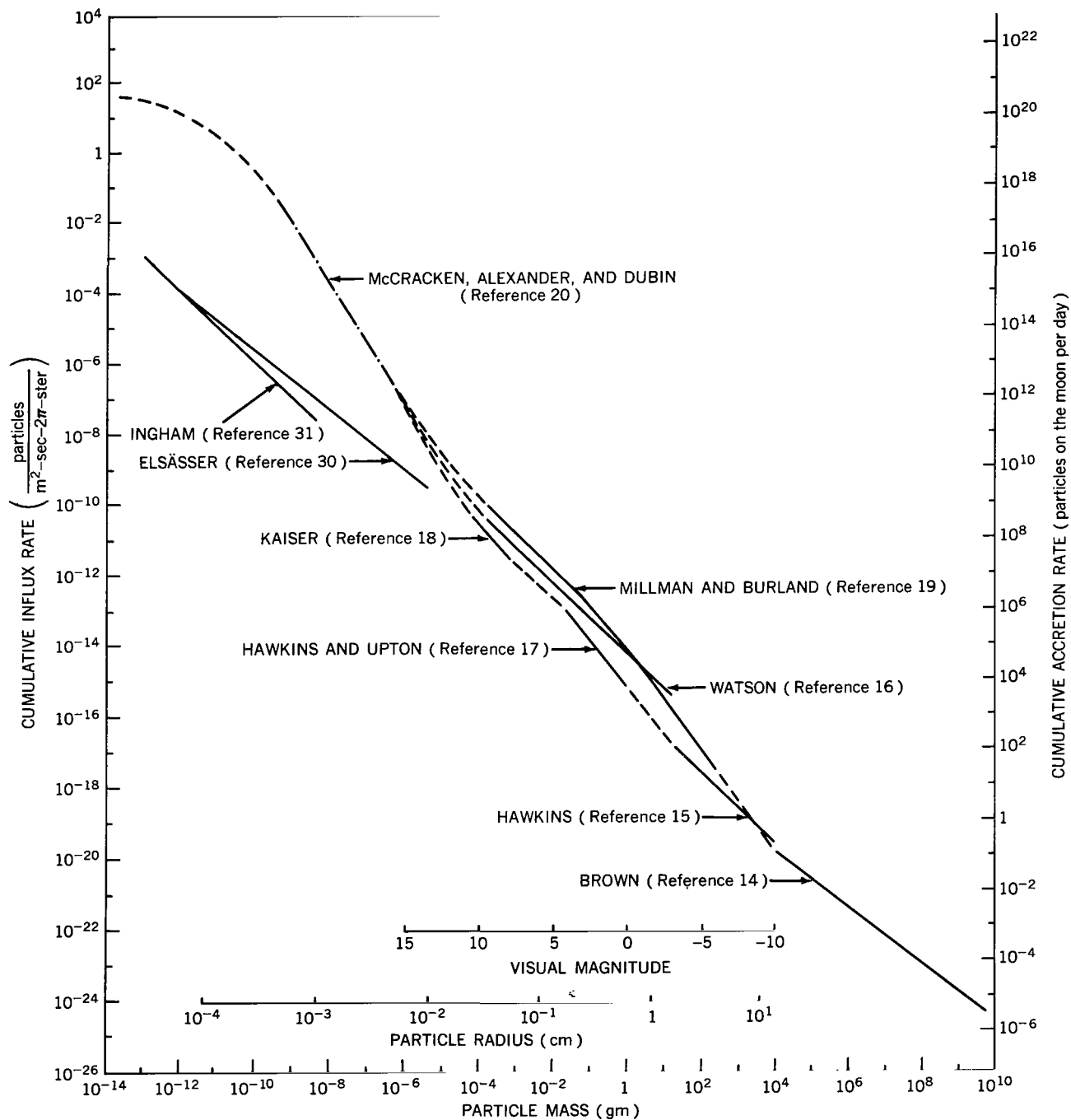


Figure 2—Cumulative mass distribution for interplanetary dust particles in the vicinity of the moon, derived from studies of meteorites and meteors and from photometric studies of the zodiacal light and the solar F corona. (The results obtained with rockets and satellites near the earth are shown for the purpose of comparison.)

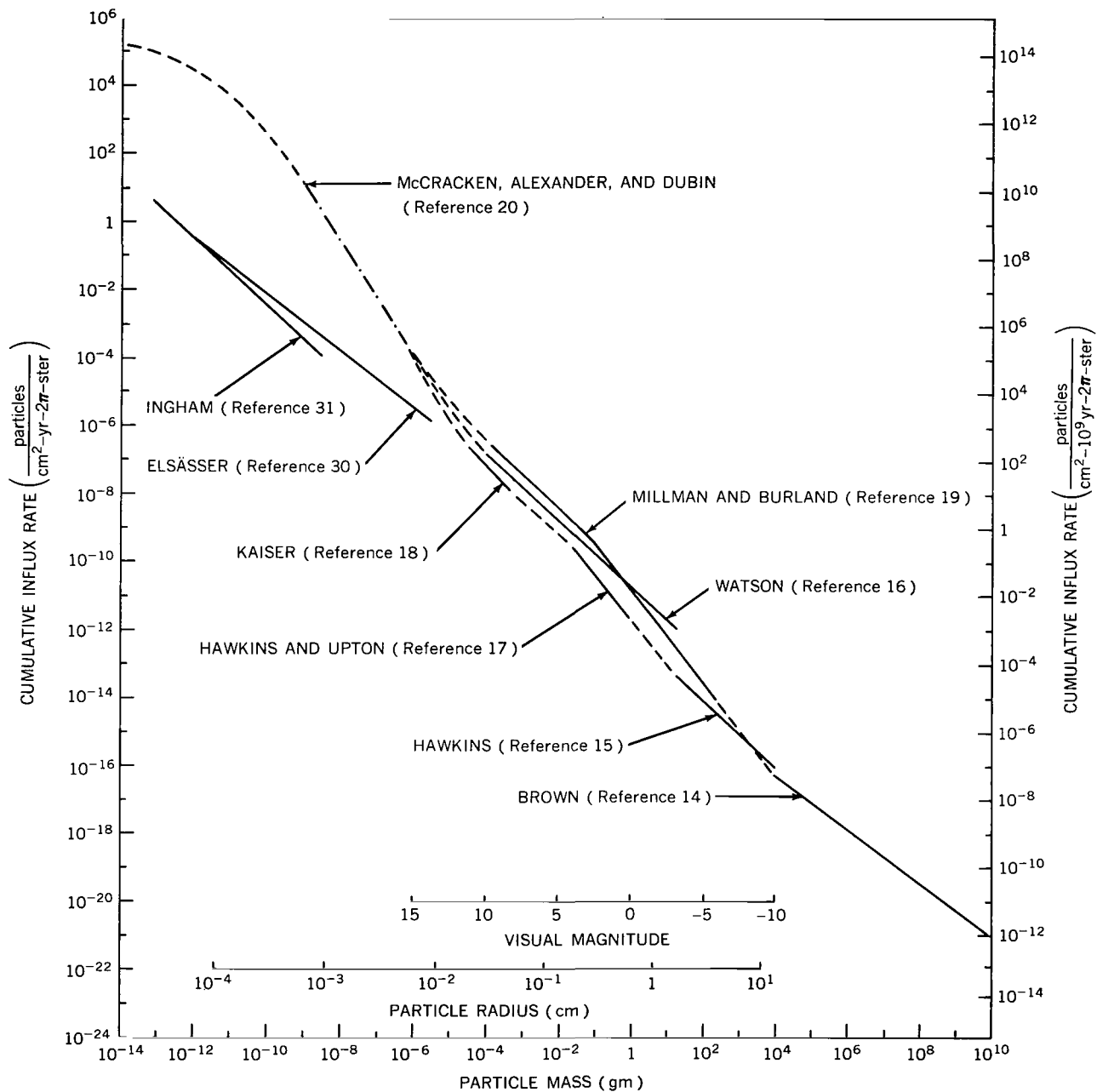


Figure 3—Cumulative mass distribution for the vicinity of the moon. (This figure is identical to Figure 2 except for the units on the ordinates.)

A useful distribution curve (which seems to show some significant trends) can be derived from the cumulative distribution shown in Figure 3. Since the derivation involves differentiation, the uncertainties which can occur when a not-too-well-known function is differentiated must be remembered. The cumulative mass distribution is first differentiated with respect to the particle mass to give an incremental mass distribution. The flux of particles having masses within an incremental range of particle mass is then multiplied by the particle mass. This operation results in the incremental mass influx distribution shown in Figure 4. The unit range of particle mass is taken to be unit magnitude, because of the extensive use of magnitude (visual) in the meteor literature. An increase of 1 magnitude corresponds to a decrease of 0.4 in the logarithm of the particle mass and to a decrease by a factor of $100^{1/5} = 2.5$ in the mass of the particle. Magnitude has no physical meaning outside the meteoroidal range of particle mass, but it can be used as a convenient logarithmic measure of the mass.

An incremental mass influx curve (similar to the one shown in Figure 4) for the vicinity of the earth shows that the process of accretion of material by the earth is dominated by particles of micron size. The incremental mass influx curve for the moon (Figure 4) shows that the particles of meteoroid size most probably represent the major contribution in the accretion of interplanetary material by the moon. This conclusion would be affected if the mass of a particle which produces a meteor of zero visual magnitude were reduced appreciably. According to Levin (Reference 32), the value of 1 gm used by Whipple (Reference 26) for the mass of a zero visual magnitude meteor should be reduced by 10 to 100 times.

The incremental mass influx curve shown in Figure 4 also can be transformed into an energy flux or a momentum flux distribution if an average speed is assumed to hold over most of the range of particle size shown. A value of about 25 km/sec would be appropriate for particles having masses less than about 10^4 gm.

The amounts of interplanetary dust accreted by the moon during a given interval of time can be computed on the basis of the mass distributions shown in Figures 2, 3, and 4. The accretion rate can be read directly from Figure 4 with an accuracy that is well within the limits of uncertainty in the observational data from which the distributions were derived. (It should be remembered, for convenience in using Figure 4, that an increase of 5 in the magnitude corresponds to a decrease by a factor of 100 in the mass of the particle.) Use of the distributions derived from the results given by Hawkins, Hawkins and Upton, Kaiser, Elsässer, and Ingham leads to an accretion rate of approximately 0.5 gm/cm² for particles with masses less than 10^4 gm incident on the moon during the past 4.5×10^9 yr. Use of the distributions of Millman and Burland, Elsässer, and Ingham leads to an accretion rate of approximately 3 gm/cm² for the same range of particle mass and the same interval of time.

An accretion rate of 1 gm/cm² for particles with masses less than 10^4 gm impacting on the moon during the past 4.5×10^9 yr is adopted here as consistent with the available data. According to Öpik (Reference 6) the lifetime of interplanetary bodies near the orbit of the earth is about 2×10^6 yr, which means that the flux has probably remained fairly constant during most of the past 4.5×10^9 yr. If the flux were lower at the present time than during the past, the accretion rate would need to be revised upward by an unknown amount.

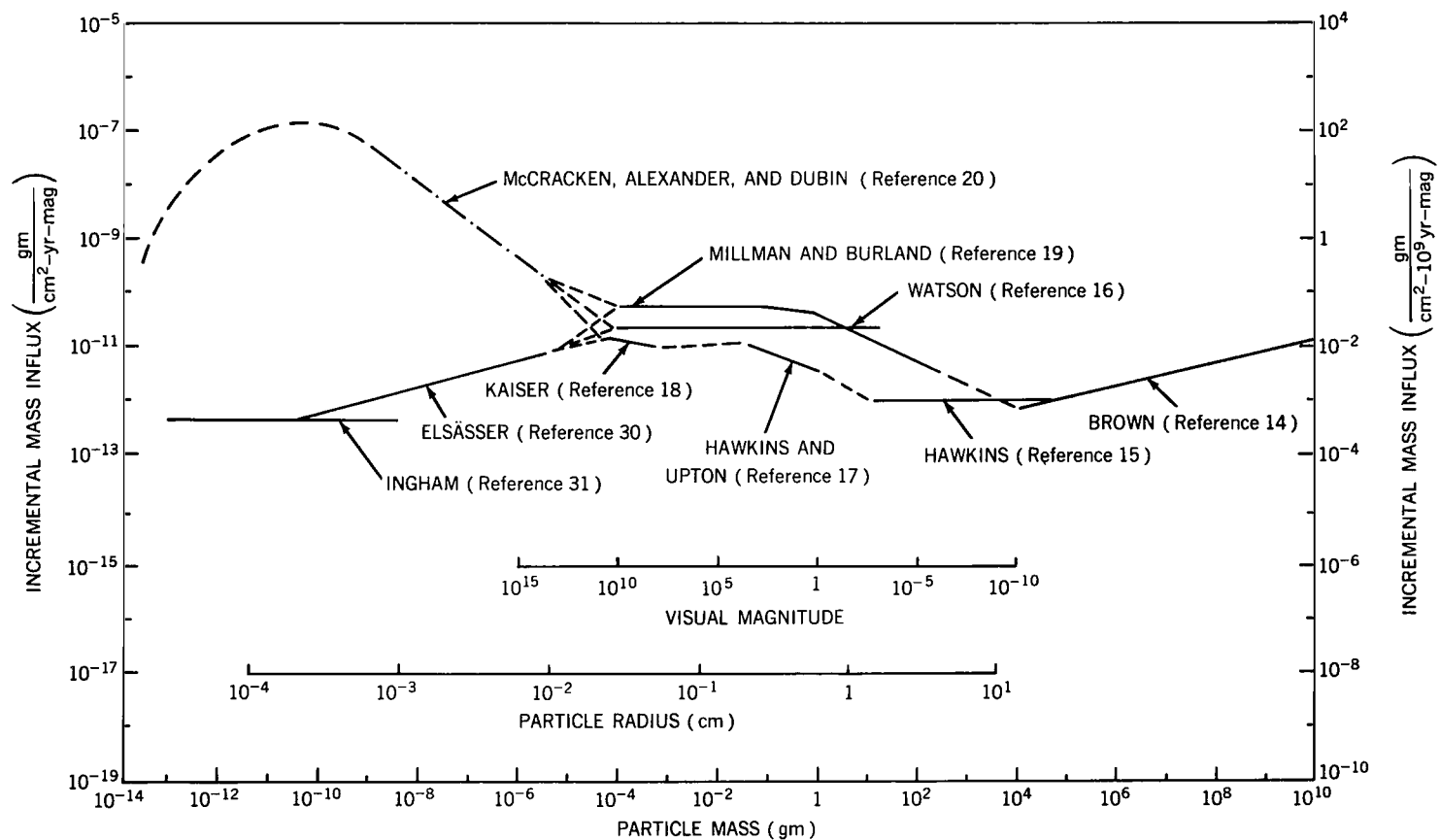


Figure 4—Incremental mass influx distribution for interplanetary dust particles impacting on the moon, derived from the cumulative mass distribution shown in Figure 2.

According to the distribution shown in Figure 4, the major contribution to the accreted material comes from particles which would produce radar, visual, and photographic meteors if they were to encounter the atmosphere of the earth. Such particles have masses between about 10^{-5} and 1 gm. Their dimensions are measured in millimeters and tenths of millimeters. Studies conducted at Harvard have shown that these particles are primarily of cometary origin and are very fragile. The mass densities of the particles are of the order of 0.5 gm/cm^3 .

A comparison may now be made between the accretion rate derived here (for particles with masses less than about 10^4 gm) and the accretion rates previously suggested by various investigators. Gold and Warner used an accretion rate of $10^{-7} \text{ cm}^3/\text{cm}^2/\text{yr}$ in considering the role of large scale dust erosion on the moon (References 33 and 34). Whipple suggested that the accretion rate was approximately $1 \text{ gm/cm}^2/2 \times 10^6 \text{ yr}$ (Reference 2). Öpik used an accretion rate of $10^{-2} \text{ gm/cm}^2/10^6 \text{ yr}$ in a discussion of the nature of the lunar surface (Reference 6). A significantly lower rate of $10^{-9} \text{ gm/cm}^2/\text{yr}$ was used by Sharanov (Reference 35). For purposes of comparison with the foregoing estimates note that the accretion rate of $1 \text{ gm/cm}^2/4.5 \times 10^9 \text{ yr}$ may be expressed also as $2 \times 10^{-10} \text{ gm/cm}^2/\text{yr}$, $2 \times 10^{-4} \text{ gm/cm}^2/10^6 \text{ yr}$, $4 \times 10^{-4} \text{ gm/cm}^2/2 \times 10^6 \text{ yr}$, and (for a mass density of 0.5 gm/cm^3) $4 \times 10^{-10} \text{ cm}^3/\text{cm}^2/\text{yr}$. The value used here is significantly lower than the values given by Gold, Whipple, and Öpik, but is comparable with the value used by Sharanov.

THE NATURE OF THE LUNAR SURFACE

An investigation of the effects of dust bombardment on the moon requires that adequate consideration be given to the physical characteristics of the lunar surface, especially on a small scale. Some parameters which are important in determining the effects of bombardment by dust particles are the composition and physical nature of the outermost lunar surface layer, the size of the surface features relative to the size of an impacting dust particle, and the interstitial nature of the grain distribution (or the porosity of the surface layer). These parameters specify the bulk density and other characteristics of the surface material. The density and structure of the impacting dust particles are also relevant in the interaction.

Some physical properties of the lunar surface have been determined by using information obtained from radar, visual, infrared, microwave, photometric, and polarimetric observations of the moon. The known properties (such as the albedo, the heat conductivity, the dielectric constant, the degree of roughness, the color, and the photometric and polarimetric properties) impose restrictions on the physical nature of the lunar surface layer. The surface can be neither smooth rock nor compacted rubble but rather must be composed of small particles arranged to have properties consistent with the observational information.

The lunar surface characteristics may be simulated by a dendriform material of low bulk density, high porosity, and a depth ranging from centimeters to several meters. The surface structure has probably developed because of the adhesive properties of micron-diameter dust particles and gas condensation in an ultrahigh vacuum. Solar radiation in the extreme ultraviolet and soft x-ray region and proton bombardment may have contributed to the adhesive properties.

The results of many of the studies of lunar surface characteristics have been reviewed and evaluated by Fessenkov, Dollfus, Sinton, and Evans (References 36-39). Öpik, Whipple, Gold, Sharanov, Sytinskaya, Troitskii, Salisbury, and others have considered the surface structure of the moon (References 1, 2, 3, 33, 35, 40, 41, and 42).

Radar observations of the moon at metric and decimetric wavelengths give information about the structure of the surface on a smaller scale than is possible with telescopic observations. Evans has recently reviewed the lunar radar results (Reference 39). Important conclusions based on radar studies are that the lunar surface is smooth and undulating with gradients of less than 1 in 10 at meter wavelengths and that less than 10 percent of the surface is covered by outcroppings with dimensions of the order of a meter. The surface is smooth down to dimensions of approximately 10 cm. Also important are the low values for the dielectric constant obtained from radar studies. These values (ranging between 1.1 and 2.7) are lower than those for ordinary terrestrial rocks, indicating a surface material of low bulk density and of a depth between a few cm and 10 m.

Results from photometric and polarimetric studies of the moon and terrestrial materials have been discussed by Minnaert, Fessenkov, and Dollfus (Reference 36, 37, 43, and 44). Some general conclusions about the lunar surface model reached on the basis of the photometric and polarimetric studies, which are important in considerations of the effects of dust bombardment, are as follows: The photometric function is nearly the same for all regions of the lunar surface, even over the range in albedo existing between the highlands and maria. Color differences on the moon are small. The moon shows no limb darkening - all points on the lunar surface reach maximum radiance near the time of a full moon. The polarization is nearly constant in magnitude and direction for the highlands but varies irregularly over the maria. The polarization varies approximately inversely with albedo. The photometric properties suggest a porous surface layer, existing even on the steepest slopes. The polarimetric results are interpreted by Dollfus and Minnaert to imply that the porous layer is covered with dust. Fessenkov is more explicit, suggesting that the surface layer may consist of agglomerations of grains.

Sinton and Zel'tser have reviewed the results of infrared measurement of the lunar surface temperature (References 38 and 45). Analyses of the temperature variation of the lunar surface lead to the conclusion that most of the surface is covered with a dust layer with a thickness greater than 5 cm.

Attempts have been made to find ordinary terrestrial materials having photometric and polarimetric properties similar to those of the moon. The attempts met with little or no success until recently. According to Minnaert (Reference 43), van Diggelen found that the photometric function of a lichen closely resembled the photometric function of the moon. An examination of the fairy castle or dendriform nature of the lichen gives an impression of how really complex the microstructure on the surface of the moon may possibly be.

The probable complexity of the lunar surface has been demonstrated more vividly in the recent successful attempts of Hapke to construct surfaces by sifting various powdered minerals (Reference 46). Using common terrestrial materials Hapke created surfaces which show photometric properties similar to those of the lunar surface. The mineral grains tend to build highly complex structures of

dendroidal form. The surfaces have irregular interstices. These experiments are the first to succeed in giving an arrangement of materials which have photometric properties similar to those of the lunar surface and which are likely to be present on the moon. The structures may also have thermal conduction properties which would explain the lag in cooling during the lunar night. Radiation damage to the mineral crystals by solar protons has been suggested as an agent for discoloring the crystals to the required opacity.

In summary, the results from the microwave, infrared, and photometric studies of the moon indicate that the surface layer is everywhere a low density porous material. The polarimetric studies indicate that a thin layer of dust exists, or (more probably) that small structures or agglomerations of particles (dendroids) cover the lunar surface. A surface layer of the complex dendriform structures created in the laboratory by Hapke will therefore be adopted in this paper as a working model for use in investigating the effects of dust bombardment on the lunar surface. It is assumed that the grain size is microscopic (of the order of 10μ) and that the grains are agglomerated into a dendroid structure. The dendroid nature of the agglomerates of dust particles results in a material of very low bulk density, probably 10 times less than the density of the parent material. The structure is effectively very open with interstitial spaces of various sizes and shapes. A depth of a few cm for the layer will serve as a starting point in the investigation.

Yet remaining, however, is the hypothesis of a mechanism on the lunar surface to act as the analog of the sifting process used in the laboratory to distribute the grains. The process must be capable of developing and maintaining the complex structures at a rate which would keep the lunar surface in a state of good repair from a photometric standpoint. Yet the mechanism must not be so dominant that it erases all photometric and polarimetric differences on the moon during a time scale of several billion years.

HYPERVELOCITY IMPACTS ON THE LUNAR SURFACE

The dendroid model of the lunar surface (described in the previous section) may have evolved during the early history of the moon at the time of formation of the maria and large craters. Following this period, dust particle bombardment could have affected the structure of the lunar surface. This is a process similar to that required to build the lunar surface. Very likely a quasi-equilibrium microstructure on the lunar surface has developed and been maintained up to the present time, if a single generation process is responsible. Although mechanisms such as volcanism and lava flows have been considered as the source of a number of lunar surface characteristics, impacts from large bodies are clearly the source of most of the craters on the moon. On a smaller scale, hypervelocity impacts by dust particles have had an effect on the surface characteristics of the moon.

The speeds (from 2.4 to 70 km/sec) for impacts of extralunar particles are catastrophically high – impacts at these velocities are called hypervelocity impacts. Speeds at the lower end of this range may be simulated experimentally by using special light-gas guns and chemical and electrical means for particle acceleration. The upper limit of speeds which have been obtained experimentally in studies of cratering is about 8 to 10 km/sec, although higher speeds can be obtained in some circumstances.

Most of the experimental data on hypervelocity impacts apply for metal targets and dense projectiles. These data are inadequate for determining the effects of impacts on the moon because great differences may be expected between hypervelocity cratering on a metal target and on a surface with the characteristics of the lunar surface. The hypervelocity interaction also depends on the density and properties of the impacting projectile. Experimental simulation of projectiles corresponding to interplanetary dust particles has not been achieved. The model for these particles is not adequately known, and the required fragility of the projectile cannot be simulated and maintained during acceleration. Some experimental data for hypervelocity impacts on rock surfaces have been obtained. The results from cratering on basalt targets are different from cratering effects observed for metals. The effects of hypervelocity impacts on sand or dust targets (and particularly on lunar-like surfaces) might be expected to differ markedly from the effects of impact on metal or basalt. The possible differences are discussed below.

A hypervelocity impact on a surface of metal or basalt forms a crater and generates high speed ejecta during the cratering process. The crater formed in a metal target is generally hemispherical; it has an edge or lip extending above the level of the target surface, and the diameter of the crater is several times greater than the diameter of the projectile. A crater is formed in a basalt target in the same manner as in a metal target, but the effect of spalling or fracturing (resulting from shock propagation in the target material) is much more pronounced. Spallation in basalt greatly increases the amount of ejecta (compared with metal targets) and accordingly increases the volume of the crater. The volume of the crater formed in sand has been found by Gault, Shoemaker, and Moore to be still larger than that formed in basalt (Reference 47).

Öpik, Bjork, and Stanyukovich and Bronshten have made theoretical studies of hypervelocity impacts in metals and rocks (References 5, 48, and 49). Bjork has probably gone furthest in solving the theory of hypervelocity cratering in metals by using a hydrodynamic model. The mechanism of crater formation is essentially one of cavitation, resulting from an intense plastic deformation wave formed during the impact. The size and shape of the crater are determined by the properties of the wave and the target material. The initial conditions applying during the early stages of the impact determine the amplitude and shape of the deformation wave. The initial stage of the impact or primary penetration is characterized by a very rapid plastic deformation of the target and impacting projectile. If the speed at impact is very high, the surface pressure so far exceeds the yield strength of the material that a hydrodynamic treatment is quite accurate. The deformation wave propagates into the target, displacing material as it disperses. The effects produced in the target depend upon the properties of the target material as described by the equation of state of the material. The crater dimensions are determined by the distance traveled by the deformation wave while its intensity is greater than the strength of the target material. The model described is essentially the same as that used by Bjork in his theoretical treatment of cratering.

The hydrodynamic model for hypervelocity impacts represents a fairly accurate approximation for impacts on metal targets. Experimental data show agreement with this model for speeds up to 11 km/sec. For the case for impacts on inelastic or brittle surface materials, the effect of shock propagation through the material results in a degree of spallation that depends on the frangibility of the target material. Experimental data for hypervelocity impacts on basalt have been obtained by

Gault, Shoemaker, and Moore (Reference 47). Craters formed by hypervelocity impacts of projectiles at velocities of 6.4 km/sec on basalt were studied in detail. The volume of the crater, expressed in terms of the cumulative mass of the material ejected from the surface, was about 200 times the projectile mass. The ejected mass was more than 10 times greater than that observed for high speed impacts in metals and represents the effects of spallation in a brittle material. The size and velocity distributions of the ejected particles were measured.

In addition to impacts on basalt, hypervelocity impacts were made on weakly bonded quartz sand. It was found that for a given expended energy, the mass ejected from the bonded sand target was at least a factor of 3 greater than the mass ejected from the basalt target. The velocity distributions of the ejected particles did not differ very much from those for basalt. For impacts on sand targets the ejected particles included grains of sand, agglomerations of sand grains, and finely crushed quartz.

Reasons exist for believing that the effects of hypervelocity impacts on a surface of dendroidal structure would be considerably different from those of impacts on metals, rocks, sand, and dust. The major difference for the dendroid model arises from the fact that this model has a compressibility. The bulk density of the dendroidal structures created by Hapke is a factor of 10 less than the actual density of the grains. An analogy for impacts into a compressible structure would be the impacts of meteoroids into a gas such as the atmosphere of the earth. In this extreme case no ejecta result, because all of the momentum is absorbed in this essentially inelastic medium. Similar effects have been observed experimentally for hypervelocity impacts into materials such as styrofoam. Projectiles with speeds of a few km per sec can be completely stopped and recovered intact. At higher speeds the projectile may fracture, but the pieces are trapped in the compressible porous matrix. Very little material is ejected by such impacts. Hypervelocity impacts and the resulting craters in metal, basalt, and a dendroidal structure are depicted in Figure 5. In the first two cases a considerable volume is ejected from the surface and the crater retains the shape formed at impact. For impacts into a dendroidal structure the projectile can penetrate deep below the surface and, while fracturing, can disperse laterally into the medium. The energy and momentum absorbed tend to expand or blow out the medium. It appears reasonable to believe that the impact will result in the raising of the surface in the vicinity of the impact without necessarily forming a crater. The hypervelocity impact would thereby lead to the generation of more small particles for building the dendroidal structure.

CONCLUSIONS

The nature of the lunar surface layer as related to the impacts of interplanetary dust particles has been an enigma. The dendroidal surface model created by Hapke successfully reproduces many of the properties of the lunar surface. It incorporates the adhesive or cemented qualities of the weak, porous matrix discussed by Whipple. It protects the underlying surface against erosion by dust particle bombardment as was suggested by Öpik for a dust layer which was not removed. Hapke has pointed out that removal of surface material by a hypervelocity impact into a dendroid layer would be inhibited.

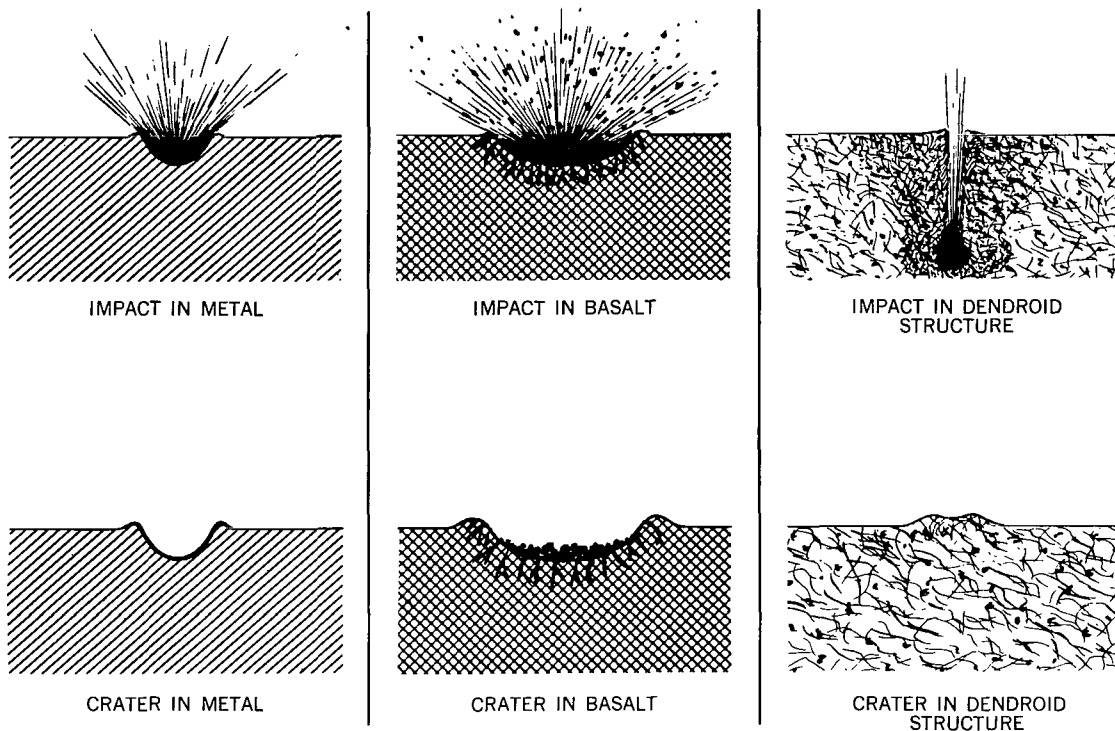


Figure 5—Hypervelocity impacts on various surfaces.

The available data on the fluxes of interplanetary dust particles with masses less than about 10^4 gm show that the material accreted by the moon during the past 4.5×10^9 yr amounts to approximately 1 gm/cm^2 if the flux has remained fairly constant. This value for the accretion rate is significantly lower than several previous estimates. The relative importance of atomic sputtering should be further investigated, because of this low value for the accretion rate.

The hypervelocity impacts of small dust particles constitute an effective mechanism for developing and maintaining a dendroid layer that is consistent with observational data for the lunar surface. The dendroid surface is probably rough on a scale that is comparable with the dimensions of the particles which dominate the accretion process. The ejecta from hypervelocity impacts on such a low density porous structure would be largely captured and retained by the surface layer, leading to positive accretion for the moon.

The lunar surface layer thus formed would consist of a mixture of lunar material and interplanetary material (primarily of cometary origin) from 10 cm to 1 m thick. The low value for the accretion rate for the small particles is not adequate to produce large scale dust erosion or to form deep layers of dust on the moon, for the flux has probably remained fairly constant during the past several billion years.

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